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BRIDGING THE GAP BETWEEN TRANSIT AND GPS POINT POSITIONING – IMPLICATIONS OF HIGHER-ORDER IONOSPHERIC REFRACTION ON THE REALIZATION OF THE WGS 84 REFERENCE FRAME

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OCTOBER 1992

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FOREWORD

This document examines the source of the scale difference between Transit and GPS satellite point positioning and infers the relationships in scale between the WGS 84 frame, as realized by its implementations through Transit and GPS satellite data reductions, and other terrestrial reference frames. The work was performed in the Space and Surface Systems Division of the Strategic and Space Systems Department and at the Defense Mapping Agency.

The authors would like to acknowledge C. Harris Seay for providing several of the simulated Doppler point positioning results used in this analysis and Bonnie Cannon for providing monthly readjustments of the Doppler network from 1987 to 1989.

This document has been reviewed by J. L. Sloop, Head, Space and Surface Systems Division.

Approved by:

R. L. SCHMIDT, Head
Strategic and Space Systems Department

ABSTRACT

This report examines the source of the scale difference between Transit and Global Positioning System (GPS) satellite point positioning and infers the relationships in scale between the World Geodetic System 1984 (WGS 84) frame, as realized by its implementations through Transit and GPS satellite data reductions, and other terrestrial reference frames. The results clearly illustrate the important distinction between the definition of a coordinate system and the realization of a reference frame.

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INTRODUCTION

The World Geodetic System 1984 Conventional Terrestrial System (WGS 84 CTS)[1] was defined by modifying the Navy Navigation Satellite System or Transit System reference frame, known as 9Z-2, in scale (-0.6 ppm), in orientation (0.814 arcsec westward rotation) and by shifting the origin 4.5 m along the negative z-axis. Analogous to the previously defined Bureau International de l'Heure (BIH) CTS, the origin of the WGS 84 coordinate system is the center of mass of the Earth; the WGS 84 z-axis is parallel to the direction of the Conventional Terrestrial Pole (CTP) for polar motion as defined by the BIH; the x-axis is the intersection of the WGS 84 reference meridian and the plane of the CTP's equator; and the y-axis completes a right-handed system.

The operational implementations of this coordinate system were accomplished by either of two procedures, depending on requirements: The first consisted of geometrically transforming previously established NSWC 9Z-2 (or WGS 72) Doppler coordinates according to the definition of the WGS 84 CTS; the second consisted of estimating coordinates from Doppler data using precise Transit satellite ephemerides provided in the WGS 84 frame. This latter procedure required that the global Doppler network of satellite tracking stations be known in the WGS 84 reference frame prior to orbit estimation. The development of these tracking station coordinates was based on an iterative procedure of successive orbit determination and point positioning with the goal of producing a self-consistent 60 station network using Transit. The resulting coordinates, chosen as the official WGS 84 station coordinate set, were consistent to within 1 m in scale and z-axis parameter and consistent in longitude, with tracking station coordinates geometrically transformed from NSWC 9Z-2.[2] An independent evaluation of the difference between transformed NSWC 9Z-2 positions and the official WGS 84 Doppler coordinates for the stations provided a mean scale difference of 78 cm.[3] This second study, however, was not based on an identical station set (50 of the original 60 Doppler stations) and used slightly different 9Z-2 starting coordinates.

The estimated coordinates for the Doppler network were adopted by the Defense Mapping Agency (DMA) for the production of precise ephemerides for the Transit satellite system on 1 January 1987.[2] Notationally, this reference frame implementation, based on Doppler data collected during 1985, will be denoted as WGS 84 D85.

As part of an operational transition from Transit to the Global Positioning System (GPS) for point positioning, the DMA adopted WGS 84 coordinates for the GPS network whose tracking data are the basis for its precise GPS ephemerides. These tracking stations were surveyed, then positioned within WGS 84, using Transit Doppler. The Doppler data survey reductions were based on Transit ephemerides produced at DMA and therefore might be expected to be on WGS 84 D85. Table 1 provides the resulting coordinates for the Air Force Operational Control Segment (OCS) stations and the DMA stations comprising the 10-station GPS network. The date of each Doppler survey is provided in the table and represents the epoch when the data were collected. Although many of the stations were surveyed prior to 1 January 1987 (as early as October 1985), Doppler data reductions for all of these stations were based on recomputed Transit orbits estimated using the WGS 84 gravity model and WGS 84 D85 tracking station coordinates. GPS satellite ephemerides estimated with pseudorange data from this network support point positioning using either accumulated phase or pseudorange observations.[4, 5]

The above circumstances, therefore, would imply that GPS point positioning results are with respect to WGS 84 D85. However, over the past several years, comparisons of GPS and Transit point positioning results have revealed systematic height differences at a number of stations.[5, 6, 7] The mean of these differences for any group of stations generally exceeds 1 m, implying that a systematic scale difference exists between WGS 84 D85 and any WGS 84 realization based on GPS.[5, 6, 7]

TABLE 1. WGS 84 DOPPLER DERIVED COORDINATES FOR OCS AND DMA GPS STATIONS

	DMA Station No.	Location	Longitude (deg)	Latitude (deg)	Height (km)	Survey Date
OCS	85128	Colorado Springs	255.4754142	38.8030569	1.91296	Oct 85
	85129	Ascension	345.5878714	−7.9513322	0.10784	Nov 85
	85130	Diego Garcia	72.3631217	−7.2665514	−0.06153	Feb 86
	85131	Kwajalein	167.7305353	8.7225006	0.04136	Apr 86
	85132	Hawaii	201.7606878	21.5614897	0.42972	Apr 86
DMA	85262	Australia	138.6547978	−34.6739325	0.03692	Sep 86
	85263	Argentina	301.4807053	−34.5737014	0.04947	Nov 85
	85264	England	358.7159244	51.4537958	0.16907	Dec 85
	85265	Bahrain	50.6081392	26.2091350	−0.01211	May 87
	85266	Ecuador	281.5064000	−0.2151528	2.92475	Feb 87

EFFECT OF IONOSPHERIC REFRACTION ON SATELLITE POINT POSITIONING

Ionospheric induced refraction, affecting observations made from orbiting satellites, has been traditionally reduced by combining measurements made at two coherent frequencies. This two-frequency measurement technique removes the greater part of this effect and provides, for instance, Doppler range differences that are significantly closer to the geometric range differences between the satellite and observing station over the observation interval, all other errors being ignored. However, residual error in range (or Doppler) measurements due to the ionosphere may have a significant effect on satellite point positioning accuracy, depending on the frequency of the satellite signal and other factors. For Transit satellite frequencies of 150 and 400 MHz, various authors have examined the structure[8,9] of this error or its impact[9,10] on Transit point positioning. Figure 1, for instance, provides examples of ellipsoidal height variations (up to 300 cm) due to higher order ionospheric effects. These results were based on simulations of point positioning, using Doppler data collected over 6-day spans.[10] It is evident from the figure that the impact of the ionosphere will depend on several factors including solar activity and location relative to the geomagnetic equator. Other factors effecting the results are the satellite's radiated frequencies and the orientation of the orbit plane to the Earth-Sun line. The correlation between time dependent variations in Doppler derived ellipsoidal heights and smoothed sunspot numbers has been examined in North America,[11] and methods have been derived to provide partial compensation for these effects.[9,11]

As a particular example of these effects, ionospheric residual range errors at Transit frequencies (computed by ray tracing through an ionospheric model at eight geographic locations) were considered.[8] The model for the ionosphere was typical of the world at 1800 UT with a Zurich sunspot number of 50. Trends in the resulting two-frequency corrected ionospheric residual range errors were functionalized with elevation angle α as the independent variable. The chosen form for the function was the simple exponential

$$r(\alpha) = ae^{-b\alpha} \quad (\alpha \text{ in degrees})$$

providing the residual range error $r(\alpha)$ in units of meters. The parameters of the model for three of the evident trends in the residual range errors were

$$\begin{array}{lll} r_1(\alpha): & a = 4.94 & b = 0.0689 \\ r_2(\alpha): & a = 2.73 & b = 0.0623 \\ r_3(\alpha): & a = 1.10 & b = 0.0523 \end{array}$$

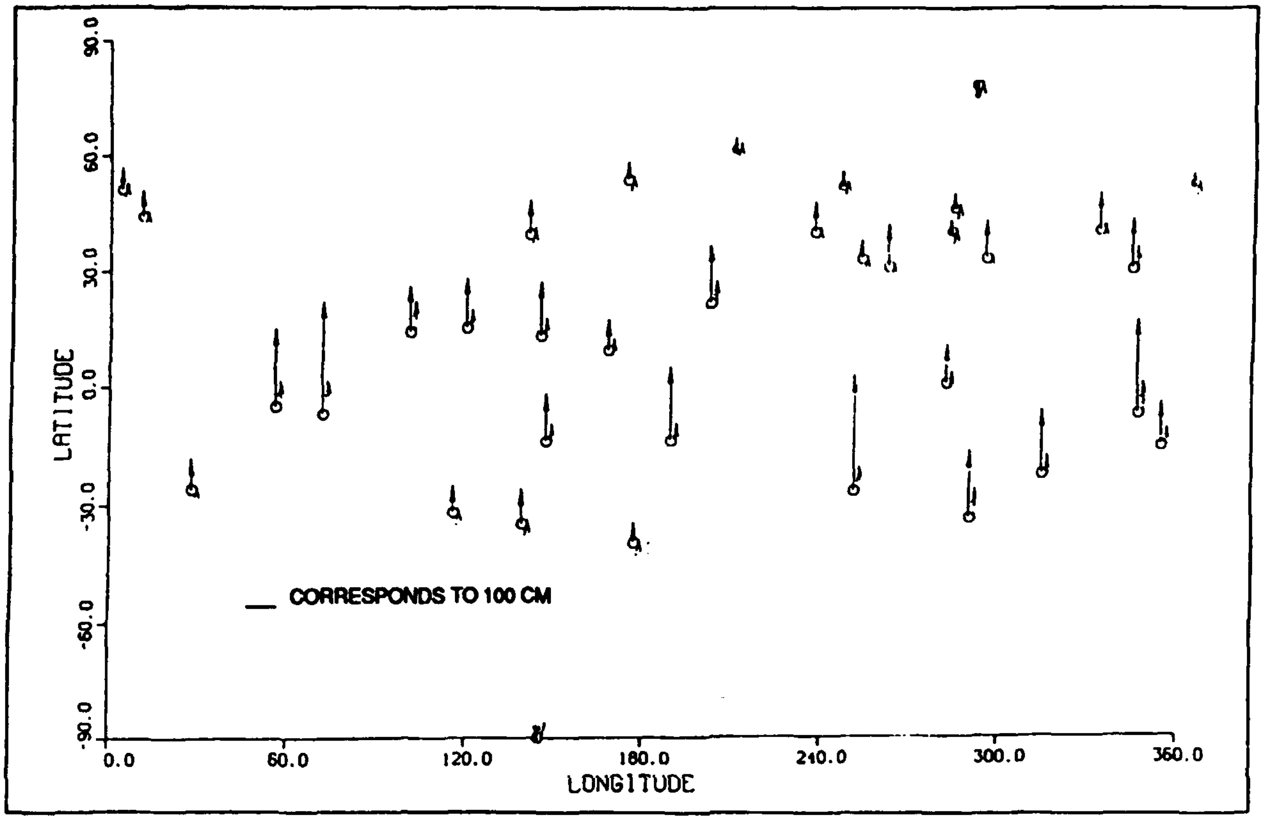

FIGURE 1. THIRD-ORDER IONOSPHERIC EFFECT ON COMPUTED STATION HEIGHTS FOR SOLAR FLUX LEVELS OF 100 AND 200

Application of this model to generate residual range difference errors for simulated Doppler data is dependent on location and local time at an observation site and on the distribution of the vertical columnar electron content within this simulated ionosphere.[8] For the two station locations chosen for this evaluation (0- and 45-deg North latitude, 280-deg East longitude), the selection of the particular model parameters a and b at any observation time was based on the global contour of total electron content for the simulated ionosphere, assuming this distribution remained fixed with respect to inertial space during the observation period. Model 1 was selected for use during hours when electron content above the station was highest; Model 3 was chosen during ionospherically quiet periods.

These residual errors were applied to Doppler range differences simulated over a 7-day interval using ephemerides for Transit Satellite 115 as computed by DMA. As a result of these errors, adjustments to the stations geodetic coordinates occur as provided in Table 2.

TABLE 2. GEODETIC COORDINATE ADJUSTMENT DUE TO HIGHER ORDER IONOSPHERIC REFRACTION

Station	Latitude (cm)	Longitude (cm)	Height (cm)
A	−6.4	18.3	149.9
B	−12.2	1.8	154.4

This example again illustrates that coordinates derived from Doppler data subject to typical higher order ionospheric refraction are systematically higher, in this case by 150 cm, than their true ellipsoidal height. These results are consistent with those previously reported, based on simulations[10] and on actual data reductions.[9]

It is particularly interesting to consider the gross effect of residual ionospheric refraction on the realization of a geodetic reference frame established using Transit Doppler. During the period from January 1987 to October 1989, coordinates for stations comprising the DMA Doppler network were individually readjusted on a monthly basis using tracking data from the last 2 weeks of each month. This readjustment served solely as a diagnostic test as the official coordinates for the network were held fixed in WGS 84 D85 for orbit production at DMA. The Transit precise ephemerides used in these adjustments were therefore in the WGS 84 D85 system by virtue of the adopted Doppler station coordinates and other WGS 84 parameters. The number of stations adjusted each month varied from an initial group of around 50 stations to a reduced set of approximately 35 stations mainly because several stations were relocated, thus breaking continuity for some of the stations in the original 1985 solution. This primarily impacted a subset of those stations not used for Transit orbit determination.

After each monthly network adjustment, a seven-parameter transformation was determined between the official WGS 84 D85 coordinates and the readjusted station coordinates. Figure 2 provides the scale changes between the WGS 84 D85 coordinates and the readjusted network every month during this period except for November 1987. The annotations are the total number of stations from the original 1985 set that were readjusted each month. These results demonstrate that subsequent adjustments of the network produced systematic scale variations in the coordinates when compared to the original scale of WGS 84 D85. The cause is unknown for the initial offset of approximately 80 cm in these results from WGS 84 D85, but is not due to ionospheric refraction, since solar activity in early 1987 was not significantly different from that during 1985 (see Figures 3 and 4).

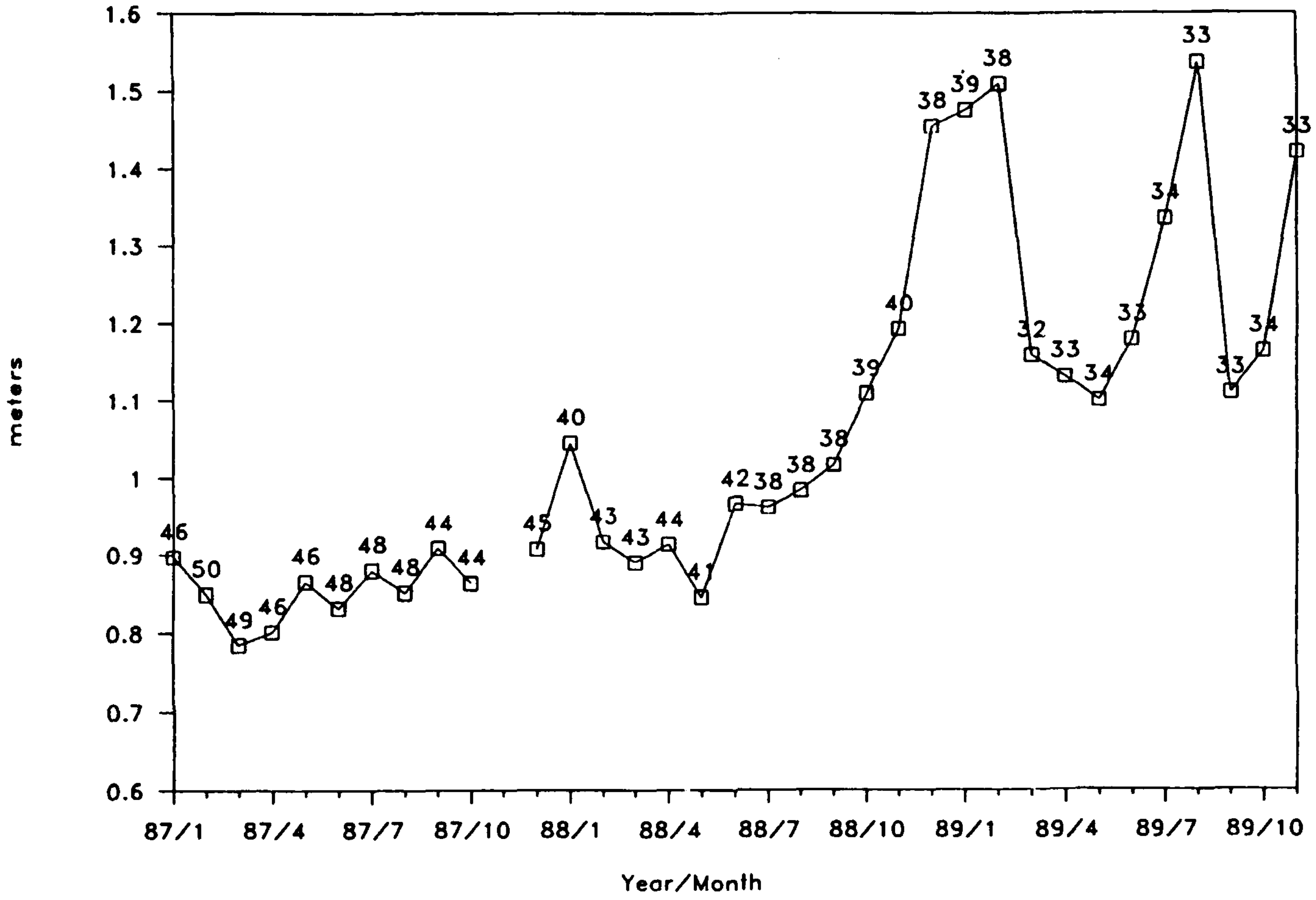

FIGURE 2. IMPLIED DOPPLER NETWORK SYSTEMATIC SCALE DIFFERENCES
JANUARY 1987 TO OCTOBER 1989

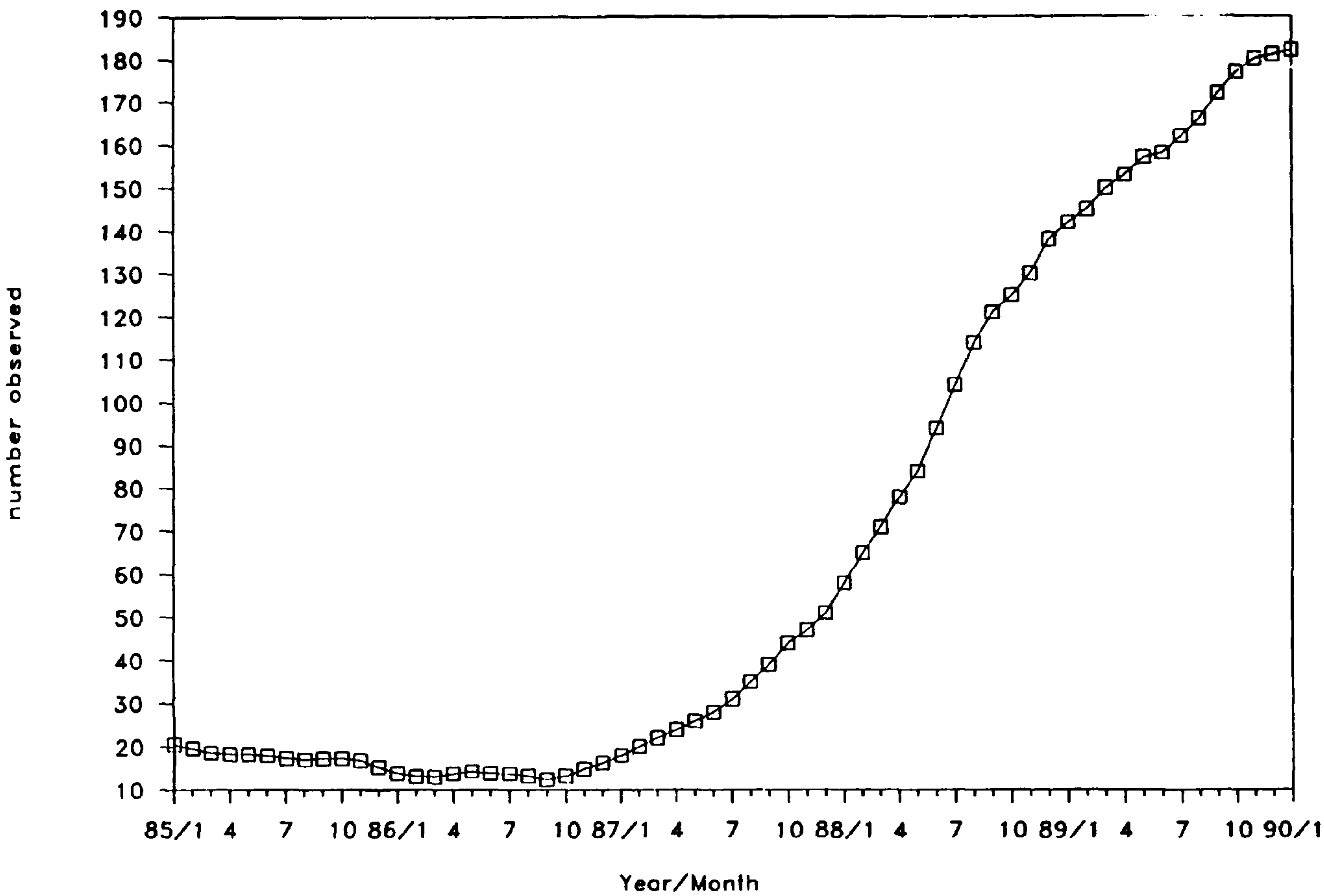

FIGURE 3. SMOOTH SUNSPOT NUMBERS
JANUARY 1985 TO JANUARY 1990

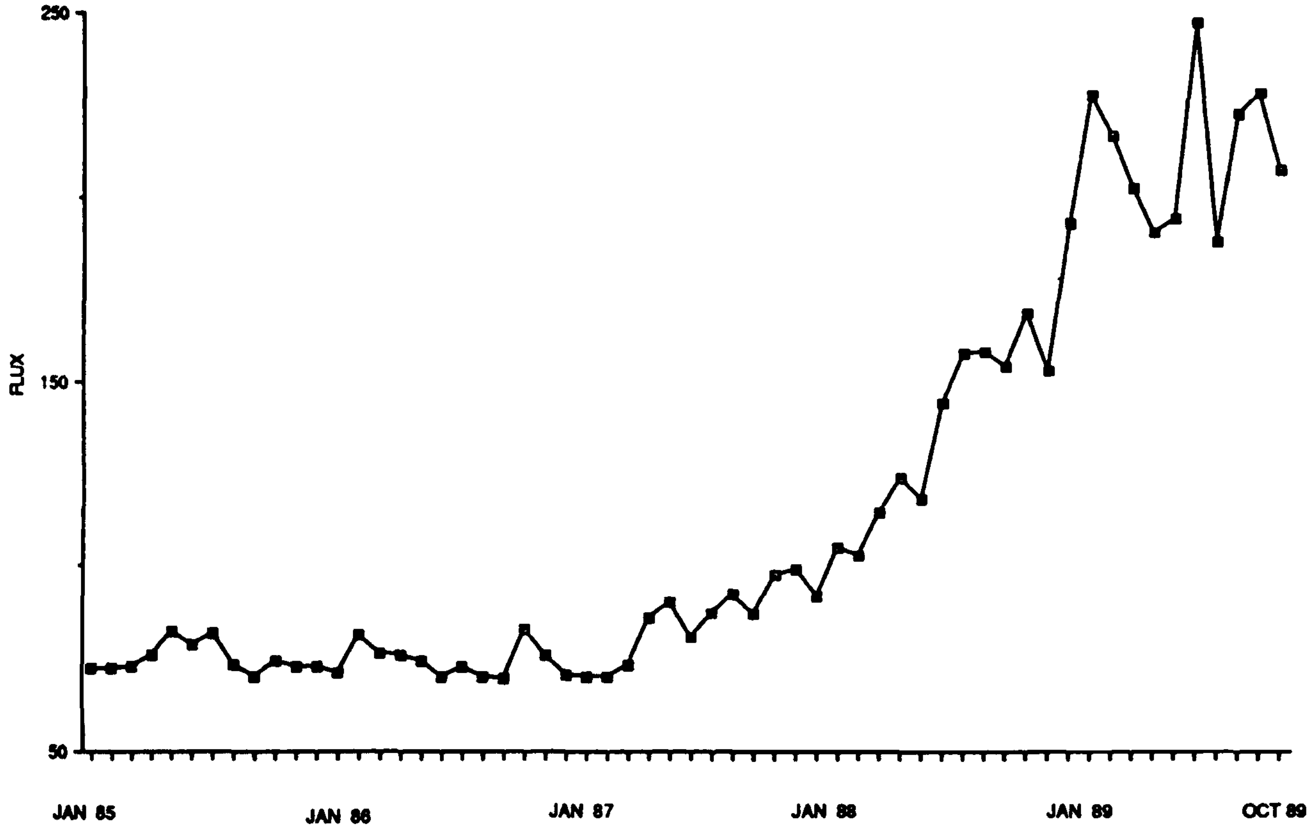

FIGURE 4. SOLAR FLUX AT 2800 MHZ—MONTHLY MEANS
JANUARY 1985 TO OCTOBER 1989

What is important is the scale variation after January 1987, ranging to 70 cm, which is highly correlated with changes in solar activity. Figure 3 provides smoothed sunspot numbers covering this period, taken from the *Solar Indices Bulletin* published monthly by the National Geophysical Data Center in Boulder, Colorado. The mean observed solar flux measured at 2800 MHz is plotted in Figure 4 for the period from January 1985 to October 1989. A comparison of Figures 2, 3, and 4 shows that there is significant correlation between changes in solar activity and the mean scale change of a readjusted Doppler network. This correlation is 0.79 with solar flux during December 1987 to October 1989 and 0.80 with smoothed sunspot numbers during January 1987 to October 1989. This, and the examples cited above, demonstrate the impact on scale of uncompensated ionospheric refraction, thus, directly limiting the fidelity of a WGS 84 CTS implementation established through Doppler techniques.

IMPACTS ON THE REALIZATION OF THE WGS 84 REFERENCE FRAME

With uncompensated ionospheric refraction impacting the heights of Doppler point positions, it is of interest to determine to what extent the scale of the WGS 84 reference frame has been impacted by such errors. This question leads to a comparison of three reference frame concepts: The first is the definition of the WGS 84 CTS; the second and third relate to attempts to realize the WGS 84 CTS through the use of the Transit System and GPS, respectively. Notations (such as WGS 84 D__ and WGS 84 G__) will be used to express such reference frame realizations. For example, WGS D85 was already defined as a particular Doppler implementation based on data collected in 1985.

The notations of Table 3 are adopted for comparisons discussed below. The designation WGS 84 D85/87 refers to the coordinates for the Air Force and DMA GPS tracking sites provided in Table 1, which were developed in the time period spanning October 1985 to May 1987. Although determined using Transit satellite ephemerides that were estimated from data collected at Doppler tracking sites whose coordinates were in WGS 84 D85, these GPS station coordinates, as a set, are biased in scale. The value for this bias was determined indirectly and is presented below.

The scale difference between WGS 84 D85 and D85/87 is due to several factors, but not primarily the ionosphere. The amount of bias due to the ionosphere would depend on the dates of survey, which are listed in Table 1, and on the variations in solar activity from that occurring during 1985 when WGS 84 D85 was established. For instance, the monthly average solar flux during 1985 varied from 72.1 in January to 72.4 in December, with a 3-month high period during May through July of 82.0, 78.5, and 81.3. Smoothed monthly sunspot numbers for 1985 showed a decreasing trend ranging from 20.5 in January to 15.3 in December. For the GPS stations positioned by Doppler, the average flux was 75.3 during data collection periods. The average sunspot number was 16.5. These averages fit within the corresponding range of values for 1985. The largest individual difference was during May 1987 when the flux and sunspot values were 89.8 and 26.5, respectively. Considering the results in Figure 2 and Figures 3 and 4, it is likely that scale variations due to solar activity were far below the changes implied by major solar variations after May 1987. Since no large variations in solar activity were present at these times, other factors must be considered to completely understand the scale difference. This is discussed further below.

Also in Table 3, WGS 84 G89 refers to a determination of coordinates for the same OCS and DMA stations using GPS tracking data[6] rather than Transit Doppler. The WGS 84 G91 is a similar GPS data solution[12] developed in 1991 at Naval Surface Warfare Center Dahlgren Division (NSWCDD). SV5 and ITRF 90 are reference frames controlled through VLBI and SLR.

TABLE 3. NETWORK REFERENCE NOTATIONS AND DEFINITIONS

Notation	Definition	Reference/Source
WGS 84 D85	Doppler Network (50 Stations), 1985 Solution using Doppler Observations	Cunningham, 1987 (Reference 2)
WGS 84 D85/87	GPS Network (10 Stations) Doppler Surveys during 1985-1987	Defense Mapping Agency
WGS 84 G89	GPS Network (10 Stations) GPS Survey	Swift, 1989 (Reference 6)
WGS 84 G91	GPS Network (10 Stations) GPS Survey	Cunningham, 1991 (Reference 12)
SV5	GPS Frame developed by MIT	Murray, 1991 (Reference 13)
ITRF 90	IERS Terrestrial Reference Frame, 1990	Boucher, 1991 (Reference 14)

From these WGS position determinations and related studies over the past several years, the question noted above regarding the impact of ionospheric refraction on reference frame development has been partially answered. Figure 5 serves to highlight what is known at this point. First, comparison of the GPS tracking station coordinates WGS 84 D85/87 with a self-consistent GPS determined WGS 84 G89 reveals that a mean height difference of 120 cm exists between the two sets of coordinates.[6] Since GPS measurements are far less susceptible to higher order ionospheric refraction, the height bias between these two systems is most likely due to height variations in Doppler positioning, from late 1985 to early 1987, caused by uncompensated ionospheric effects.[15] A similar result of 130 cm has been reported after comparison of WGS 84 D85/87 and the WGS 84 G91 coordinate set.[12] Assuming that variations in the scale of the reference frame, as evidenced by Doppler comparisons (Figure 2), are applicable to the 10-station OCS/DMA network, then the GPS-based WGS 84 implementations are more consistent with the definition of the WGS 84 CTS than are either WGS 84 D85 or D85/87. An initial comparison between WGS 84 D85/87 and SV5[16,17], using 3 weeks of GPS data collected during the International Earth Rotation Service GIG 1991 campaign, indicates that the former system has an average height bias of 141 cm with respect to the SV5 reference frame designed by the Massachusetts Institute of Technology for monitoring crustal deformation.[13] The SV5 reference frame has been tied to the VLBI/SLR frame through a number of local ties between GPS Rogue receivers and VLBI instrumentation. Another comparison between the VLBI/SLR network and the five DMA GPS tracking stations in WGS 84 D85/87 gives 140 cm for the mean scale bias.[18]

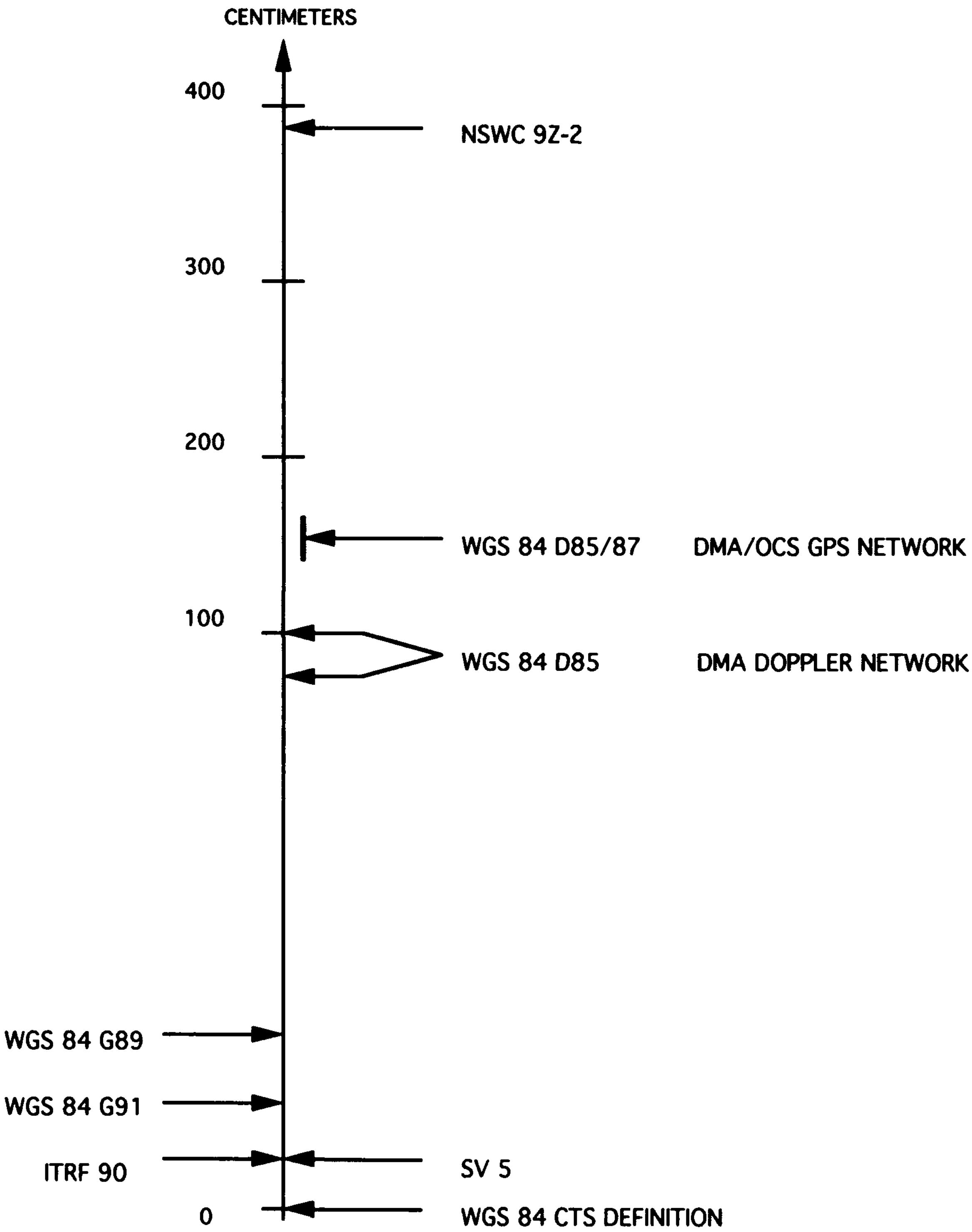

FIGURE 5. REFERENCE FRAME SCALE RELATIONSHIPS

To further assess the nature of the systematic differences between Transit and GPS implementations of WGS 84, a set of 16 globally distributed stations were positioned using both Transit Doppler[19] and GPS carrier phase[20] point positioning techniques. Standard DMA precise Transit and GPS ephemerides were held fixed in the point positioning estimation processes. In the GPS case, the precise satellite clock states were also held constant. The Transit positions were estimated from data collected during the period 1985 to 1992. The GPS positions were estimated from data especially collected for this purpose during the period 1988 to 1992. The GPS ephemerides and clocks used in the data reductions were estimated with the WGS 84 D85/87 Doppler-derived coordinates of the 10 tracking stations held fixed. Therefore, the GPS positions derived from these estimates are not statistically independent from errors in this particular realization of WGS 84.

The collocated station sets used in this direct comparison are given in Tables 4 and 5. A similarity transformation between the two sets of coordinates yielded the seven parameters shown in Table 6. A comparison of these parameters with their standard deviations indicates that scale is the one of the seven parameters that can be considered the most statistically significant. This scale parameter (-0.164 parts per million) corresponds to 1.05 m at mean Earth radius. The standard deviation on the determination of this parameter corresponds to 17 cm. When the estimation of this similarity transformation was performed, the adopted uncertainties (1 sigma) for the station coordinates were 45 cm for all components except the GPS z-components that were assigned an uncertainty of 30 cm. A smaller standard deviation on the z-coordinates derived from phase data has been empirically demonstrated[20] and is believed to be a result of the predominate north-south motion of the GPS satellites relative to a fixed terrestrial point. The resulting standard error of fit (the *a posteriori* variance of unit weight) was 1.01. The 16 stations used resulted in 41 degrees-of-freedom in this adjustment.

As corroborated by other results presented herein, the sign of the scale difference places the Transit determined ellipsoid heights above those determined by GPS. This can also be seen by a simple inspection of the height components in Tables 4 and 5. A straightforward difference of the height components in these tables yields a mean value of 1.08 m, with a standard deviation of 66 cm. This result is less than the 120 to 130 cm scale differences obtained previously; however, those solutions were a result of simultaneous adjustments of GPS orbits, clocks, station coordinates, and other parameters, such as zenith tropospheric delays. The 12 to 22 cm disparity between these point positioning results and other results presented herein could certainly be explained by these significant differences in estimation algorithms. It is also noteworthy that, when orbits are held fixed, only a fraction of any radial orbit error propagates into an estimated point position.

TABLE 4. WGS 84 TRANSIT POINT POSITIONING RESULTS USING DOPPLER

Location	Longitude (deg)	Latitude (deg)	Height (km)
Albrook	280.44170917	8.98786306	0.073460
Smithfield	138.65479780	−34.67393250	0.036690*
Argentina	301.48070530	−34.57370140	0.049240*
England	358.71592440	51.45379580	0.168840*
Bahrain	50.60813920	26.20913500	−0.012340*
Ecuador	281.50640000	−0.21515280	2.924520*
Pueblo	255.70806528	38.43652583	1.501730
Albuquerque	253.34695972	35.05620778	1.485674
Dodge City	259.99250028	37.75115250	0.732922
Falcon AFB	255.47541694	38.80311750	1.911650
Platt	255.27366333	40.18279444	1.503180
Portugal	332.90967890	38.77533056	0.108937
Oman	57.45144250	19.03830861	0.004016
Ascension	345.59792100	−7.90784700	0.040715
Kinshasa	15.25513600	−4.37043400	0.453526
Sheyma	174.10109556	52.72878722	0.078560

* Height to antenna base, not electrical center, as in Table 1.

TABLE 5. WGS 84 GPS POINT POSITIONING RESULTS USING PHASE

Location	Longitude (deg)	Latitude (deg)	Height (km)
Albrook	280.44170667	8.98786389	0.072010
Smithfield	138.65479500	−34.67393139	0.035523
Argentina	301.48070694	−34.57369861	0.049086
England	358.71592444	51.45379028	0.167742
Bahrain	50.60814028	26.20913833	−0.013810
Ecuador	281.50639722	−0.21515389	2.923127
Pueblo	255.70806556	38.43651833	1.500867
Albuquerque	253.34695889	35.05619972	1.485436
Dodge City	259.99250528	37.75114361	0.732775
Falcon AFB	255.47539581	38.80311903	1.910677
Platt	255.27366320	40.18279398	1.501560
Portugal	332.90967189	38.77534075	0.106671
Oman	57.45143422	19.03831714	0.002995
Ascension	345.59792111	−7.90785111	0.040521
Kinshasa	15.25514306	−4.37044028	0.451354
Sheyma	174.10110083	52.72878472	0.077538

TABLE 6. SIMILARITY TRANSFORMATION BETWEEN WGS 84 TRANSIT AND GPS POINT POSITIONING RESULTS FROM TABLES 4 AND 5

	X (cm)	Y (cm)	Z (cm)	L ($x10^{-6}$)	ω	ψ (marcsec*)	ε
Parameter	−21	−11	−7	−0.164	1.3	2.7	−7.5
Sigma	18	18	16	0.027	6.7	7.2	6.4

* The angles ω, ψ, and ε are around the Z-, Y-, and X- axes, respectively.

CONCLUSIONS

The results presented in this report clearly illustrate the important distinction between the definition of a coordinate system and the realization of a reference frame.[21] The WGS 84 coordinate system was adopted in both Transit and GPS point positioning techniques, yet these techniques yield two distinct realizations of the WGS 84 reference frame due to ionospheric refraction and other factors, such as the propagation of orbit error into station positioning.

The relationships in scale between the various frames discussed above are summarized in Figure 5. Based on two studies, the metric scale difference between the WGS 84 CTS definition and the WGS 84 D85 frame is on the order of from 78 to 100 cm (in the figure, refer to the two arrows associated with the DMA Doppler network).[2,3] Second, since the GPS tracking stations were positioned by Doppler over a period spanning October 1985 to May 1987, height errors at individual stations have led to a WGS 84 D85/87 system with a mean scale above that of WGS 84 D85. One factor in this difference is sample size. The GPS network consists of only 10 stations. Thus, the effect of random positioning errors (1 to 1.5 m in each component for Doppler positioning) on the mean scale may be much greater than on that of a Doppler network with 50 to 60 stations. Third, based on adjustments comparing WGS 84 D85/87 with a reference frame closely tied to VLBI/SLR (References 17 and 18), using data from either all or from a partial (5-station) set of OCS/DMA GPS stations, it is probable that WGS 84 D85/87 lies 50 to 60 cm in scale above WGS 84 D85 or 150 to 160 cm above the WGS 84 CTS definition, as illustrated in Figure 5. Fourth, comparisons of GPS positioning solutions for the OCS/DMA stations with WGS 84 D85/87 imply that a GPS-based implementation of the WGS 84 reference frame would result in scale consistency with VLBI/SLR to within 10 to 20 cm. In Figure 5, ITRF 90 and SV5 are considered equivalent in scale.

While uncompensated ionospheric refraction appears to be the primary factor responsible for the distinct realizations of scale seen in WGS 84, other factors may also play a significant role. For example, an error in the adopted value of GM will propagate into position estimates using either Transit or GPS ephemerides. Since Transit and GPS satellites are at significantly different altitudes, this error source affects the two satellite positioning methods differently. While quantification of this effect was not considered in this study, it helps underline the complexities of reference frame development and maintenance.

Other conclusions and recommendations that can be drawn from the analysis to date are as follows:

- The direct implementation of WGS 84, using its definition as applied to a network of NSWC 9Z-2 Doppler station coordinates, provided a system whose scale was less impacted by ionospheric refraction than the reestimated coordinates of the Doppler network, WGS 84 D85. It is assumed that the scale correction (-0.6 ppm) adopted for the WGS 84 CTS largely compensated for this effect, since that scale correction was indicated from comparisons with VLBI and SLR.

- The WGS 84 D85/87 system of GPS tracking station coordinates obtained with Doppler is not consistent with WGS 84 established by GPS, is biased in scale, and should be replaced based on a readjustment using GPS data alone. The systematic scale difference due to uncompensated ionospheric refraction of Transit Doppler is the primary reason for the observed height bias between Doppler and GPS positioning seen at many locations.

- The preliminary GPS solutions for the coordinates of the GPS tracking stations, WGS 84 G89 and G91, are much more consistent in scale with VLBI/SLR. These preliminary solutions are being refined. Additional comparisons between WGS 84 and VLBI/SLR based frames, using GPS observations, will further clarify systematic scale differences.

- The WGS 84 CTS definition appears to be consistent in scale with ITRF 90 to the 10-cm level.[14]

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